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# End User Impacts of Automated Electrochromic Windows in a Pilot Retrofit Application

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**Abstract**

Automated electrochromic (EC) windows, advanced thermally-improved window frames, and a dimmable lighting system were installed in a single, west-facing conference room in Washington DC. The EC windows were commercially-available, tungsten-oxide switchable devices, modulated automatically between either fully clear or fully tinted transparent states to control solar gains, daylight, and discomfort glare. Occupants were permitted to manually override the automated EC controls. The system was monitored over a 15-month period under normal occupied conditions. The last six months were used in the analysis. Manual override data were analyzed to assess the EC control system design and user satisfaction with EC operations. Energy and comfort were evaluated using both monitored data and simulations.

Of the 328 meetings that occurred over the six month period, the automatic system was manually overridden on 14 or 4% of the meetings for reasons other than demonstration purposes. When overridden, occupants appeared to have switched the individual zones with deliberation, using a combination of clear and tinted zones and the interior Venetian blinds to produce the desired interior environment. Monitored weekday lighting energy savings were 91% compared to the existing lighting system, which was less efficient, had a higher illuminance setpoint, and no controls. Annual performance was estimated using EnergyPlus, where the existing condition met the ASHRAE 90.1-2007 prescriptive requirements except for a higher window U-value. Annual energy savings were 48% while peak demand savings were 35%.

*Keywords:* Electrochromic windows; Daylighting; Control systems; Building energy efficiency; Intelligent buildings; Integrated systems

## 1. Introduction

Large-area, switchable electrochromic windows have been transitioning from the laboratory to the marketplace over the past few decades. These multi-layer window coatings have variable solar and optical properties that can be modulated with a small applied voltage. When coupled with advanced thermally-improved window framing, this dynamic, highly-insulating window will play an essential role in achieving low energy use goals in the residential and commercial building sectors [1,2]. In 1969, Deb [3] exhibited the first switchable electrochromic (EC) device in the laboratory. Small-area prototypes gradually improved in the ensuing decades, moving from 2 cm (0.79 in.) samples with a small switching range and

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limited cycling capabilities to 0.3 m (1 ft) then 1 m (3.28 ft) square samples with a broader switching range and more extended cycling capabilities. In the late 1990s, a handful of developers in the US responded to a request for qualifications issued by the US Department of Energy (DOE). The selected developer who met basic size, switching range, and durability tests was then invited to participate in a more in-depth collaboration with DOE National Laboratories to help accelerate adoption of the technology into the market. An extensive battery of tests was conducted by the National Renewable Energy Laboratory to evaluate durability of the devices. Full-scale field studies were initiated at the Lawrence Berkeley National Laboratory (LBNL) with 43x85 cm (17x33 in.) EC prototypes assembled to create a large-area window, then automatically controlled in combination with a dimmable lighting control system [4]. The system was monitored in a full-scale, south-facing, outdoor office mockup over several solstice-to-solstice periods to assess energy and comfort performance. Since this field study, EC windows have been installed in buildings throughout the US as manufacturers continued to make inroads into the marketplace.

The technical potential of switchable windows to reduce energy use, peak demand, and improve indoor environmental quality and user comfort has been estimated to be significant. There is, however, a general lack of measured data in the field under realistic occupied conditions. A few full-scale human factors studies have been conducted over a short period per subject with and without automated EC controls [5-7], but long-term post-occupancy evaluation studies are needed to better understand user acceptance and satisfaction with automatically-controlled EC windows.

This study summarizes the findings from a pilot demonstration of tungsten-oxide, large-area, electrochromic windows with automated controls in a west-facing conference room in Washington DC. The EC windows were automatically controlled in an on-off, fully clear or fully tinted mode. A dimmable lighting system was also installed. The system was monitored over a 15-month period with the last six-month, solstice-to-solstice period analyzed for performance. The analysis focuses on the unique aspects of this demonstration: a) manual overrides of the automated system as a means of understanding user satisfaction with the automatically controlled EC windows, b) methods of running fault detection and diagnostics on monitored data, and c) monitored lighting energy use. Spot surface temperature measurements were made on site, with additional EnergyPlus comparisons of interior surface temperatures of the existing and retrofit windows. Total annual energy use and peak demand were also computed using EnergyPlus.

## 2. Physical systems

### *2.1. Room description*

The pilot demonstration occurred in a single, west-facing, 5.94 m wide by 4.57 m deep by 2.74 m high (19.5 x 15 x 9 ft) conference room located on the sixth floor of a seven-story office building in Washington DC (Figure 1). The existing conventional single-pane windows and lighting system were replaced with commercially-available, dual-pane EC windows and a dimmable lighting system. The interior of the conference room had light gray walls, a dark gray carpet, and a white acoustical tile ceiling. Furnishings included a large wooden conference table and chairs. There were two entry doors: one leading to an open plan interior work area, the other leading to an adjacent office. Space conditioning was provided through the overhead diffusers with supplementary space conditioning provided by a convector unit at the perimeter windows (air was blown at a 45° angle away from the window).

### *2.2. Window condition*

There were two west-facing windows in the conference room. Each existing window was 2.24 m wide by 1.99 m high (7.35 x 6.54 ft) with two, equal area lites separated vertically. The windows were separated by a 0.73 m (2.4 ft) wide opaque wall. The sill height was 0.76 m (2.5 ft). The existing windows had single-pane, bronze tinted glass with an applied window film and a non-thermally-broken aluminum frame. Since the exact glass type was unknown, National Fenestration Research Council (NFRC) whole window properties were estimated using Window 5 [8] assuming a conventional 6 mm (0.25 in.) thick bronze glass typical of this building vintage and the known window film properties: visible transmittance, Tv = 0.36, solar heat gain coefficient, SHGC = 0.36, U-factor = 5.33 W/m$^2$-°C (0.94 Btu/h-ft$^2$-°F). The window-to-wall area ratio (WWR) was 0.40. ASHRAE 90.1-2007 [9] prescriptive requirements sets a maximum assembly SHGC and U-value of 0.40 and 2.27 W/m$^2$-°C (0.40 Btu/h-ft$^2$-°F), respectively, for WWR less or equal to 0.40.

**Fig. 1.** Interior view of the conference room with upper and lower control zones.

The existing windows were replaced with switchable, tungsten-oxide, electrochromic windows and thermally-broken framing. The insulating glass units consisted of an outboard, 6 mm (0.25 in.) thick, tempered electrochromic glazing layer (Sage Electrochromics), a 12.7 mm (0.5 in.) wide argon-filled (90%) gap, and an inboard laminated glazing layer consisting of a 0.8 mm (0.03 in.) clear PVB interlayer sandwiched between two layers of 3 mm (0.125 in.), clear, heat-strengthened glass. Warm wall edge, stainless steel spacers were used. The framing system was an advanced, thermally-broken aluminum frame (TRACO) with a thermal break gap of 2.3 cm (0.9 in.), a low-e coating on the interior aluminum surface, and aerogel foam filling in the frame cavity. The EC windows were controlled to either the fully clear or fully tinted state. Whole window values for these two states were: visible transmittance (Tvis) = 0.50 or 0.03, solar heat gain coefficient (SHGC) = 0.39 or 0.08, and U-factor = 1.93 W/m$^2$-°C (0.34 Btu/h-ft$^2$-°F). When switched, the tint of the window was a deep Prussian blue.

Each EC window was subdivided into an upper and lower zone, consisting of two panes per zone (Figure 1). Each upper pane was 1.06 m wide by 0.61 m tall (3.46 x 1.99 ft). Each lower pane was 1.06 m wide by 1.26 m tall (3.46 x 4.12 ft) subdivided by a thin horizontal bus bar in the middle of the glazing (0.63 m, 2.07 ft from the edge). The upper panes of the two windows were grouped into one automated control zone. The lower panes were grouped in a similar way.

The windows were recessed approximately 0.3 m (1 ft) from the exterior face of the building where the four exterior surfaces surrounding the window were splayed to form a slightly larger opening on the exterior face of the building. The splayed surfaces surrounding the window were a light beige colored concrete. There was a seven-story office building across the street: solar profile angles less than approximately 15-20° would be blocked by this opposing building.

The automated control algorithm was specified by LBNL to minimize seasonal heating and cooling loads, provide daylight, and minimize the effects of direct sun and discomfort glare. When occupied during the day, the upper EC clerestory zone was switched to provide daylight and the lower zone was switched to minimize discomfort glare. When unoccupied during the day, the smaller upper windows were switched to clear or tinted to minimize heating and cooling loads, respectively, and the lower larger windows were switched to tinted in anticipation of being required to switch quickly to tinted to reduce discomfort glare:

tinting can take some time during cold winter conditions (see Section 3.3). During the night, all windows were switched to clear.

The EC manufacturer placed a limit on how long the EC windows could be tinted, causing the EC windows to switch to clear for a 14 h "rest period" after 10 h/day of being tinted. During this lock-out period, the EC windows could not be switched to tinted irrespective of automated or manual control. This tint limit was imposed to preserve the long-term durability of the EC multi-layer coating. For this west-facing window, a start and end time for the 10-h period was specified in the automated control system corresponding to the likely period of occupancy and anticipated low-angle solar control needed at sunset, especially on the longer, brighter days of summer. Since occupancy was typically within the hours of 9:00-18:00 LT with occasional evening meetings, the 10-h period was set to 9:00-19:00 LT. Sunset occurred around 16:40-17:30 LT/ST during the winter and 17:00-18:20 LT/DST during the summer so this defined period adequately covered the afternoon to evening summer period.

Table 1 summarizes the inputs and outputs to the automated control system. Table 2 summarizes the various states of automated control. The algorithm was then implemented by the manufacturer as an executable control module within the National Instruments LabVIEW data acquisition and control system. Inputs from the occupancy sensor, an exterior vertical light level sensor, and time of day schedules were used for control. The exterior vertical light level sensor was an interior skylight sensor (PLC Multipoint MAS/S) adapted for exterior use. Its signal is denoted by Sv. The sensor was mounted so that the white plastic domed lens faced outward, normal to the surface of the window. The blue-enhanced photodiode had a 1-s response time, 1 to 107,600 lux (1 to 10,000 fc) range, -40–60°C (-40–140°F) operating temperature, and ±2% linearity at 21°C (70°F). Because the sensor was designed to measure light level but not illuminance precisely, sensor data will be given without the nominal units (fc) to avoid confusion with illuminance data.

Four switches corresponding to each of the four window zones (left and right window, upper and lower zones of each window) were mounted on the interior wall between the two windows to enable the occupants to override the automatic control system.

*2.3. Dimmable lighting*

The existing lighting system consisted of (12) 0.30x1.2 m (1x4 ft) fixtures with (2) T8 lamps per fixture (estimated 60 W per fixture) and electronic ballasts with an estimated installed lighting power density (LPD) of 26.5 W/m$^2$ (2.46 W/ft$^2$). Manual switches enabled the occupants to turn on and off the lights as a single zone. These switches were located either inside or outside the room and may have been linked to the lighting in the work area outside the conference room. One building occupant recalled that the conference room and common space lighting were switched on all day. There was no occupancy sensor in the conference room.

The existing lighting was replaced with (6) 0.61x0.61 m (2x2 ft) direct/indirect recessed fixtures (Lutron EcoSystem) with (2) 24 W, T5HO lamps (3500°K) and digitally-addressable, dimmable ballasts (Lutron EcoSystem EC5). The installed lighting power density was 11.2 W/m$^2$ (1.04 W/ft$^2$). Lighting energy use ranged from approximately 53-303 W for a light power output range of 17-100%. Standby power use when the lights were shut off was 9 W. The average workplane illuminance on the conference room table was measured at 355 lux (33 fc) after six months of operation.

An ultrasonic and passive infrared occupancy sensor (Lutron LOS-CDT) and photosensor (Lutron C-SR-M1) were mounted on the ceiling. The ceiling-mounted photosensor was located 2.6 m (8.5 ft) from the window, centered between the two windows, and directed to face the rear east wall. One manually-operated keypad near each of the two entry doors enabled users to select one of four preset interior lighting levels or turn the lights off. The lighting control system (Lutron Grafik Eye QS) switched the lights off after the occupants vacated the room for 8 min. The lights were automatically dimmed to supplement the available daylight in order to meet the preset illuminance level selected on the keypad. For daylighting, the digital lighting system was zoned to dim each of the three fixtures nearest the window independently and dim the three fixtures furthest from the window as a single grouped zone.

**Table 1. Input and outputs of EC automated control system**

| | | |
|---|---|---|
| **Inputs** | | |
| Exterior vertical light level sensor, Sv * | | 0-10,000 |
| Time of day (real-time astronomical clock) | | 0:00-23:59 |
| Day of year | | 1-365 |
| Occupancy (Lutron sensor), 1=occupied | | 0,1 |
| **Setpoints** | | |
| Start time of period allowing EC to tint (LT = local time) | | 9:00 LT |
| End time | | 19:00 LT |
| Cooling season start date | | May 1 |
| Heating season start date | | October 1 |
| Delay when enter to update auto control | | 10 s |
| Delay when leave to return to auto if manually overridden | | 2 min |
| Exterior vertical light level sensor, Sv: | specified | actual (8-bit value) |
| Threshold to tint, upper zones 2&4 | 3000 | 3007 |
| Threshold to clear, upper zones | 2700 | 2716 |
| Threshold to tint, lower zones 1&3 | 1800 | 1794 |
| Threshold to clear, lower zones | 1600 | 1600 |
| Delay switching to clear once crossed lower threshold | | 10 min |
| **Outputs and logged data from EC controller** | | |
| Automated control action (0=clear, 1=tint, -1=no action) | | 0,1,-1 |
| Manual override action (0=clear, 1=tint, -1=no action) | | 0,1,-1 |
| EC status of each window pane (0=clear, 1=tint) | | 0,1 |
| Time EC pane in clear state | | 0-36,000 s |
| Time EC pane in tinted state | | 0-36,000 s |

* Exterior vertical light level sensor, Sv, provides readings in nominal footcandles but is given as unitless values in this paper to avoid confusion with accurately measured illuminance data.

**Table 2. States of the EC automated control system**

| State | Occupancy | Season C=cooling H=heating | Sun up? | N Period 9-19:00 LT? 10h switch limit | Exterior vertical light level, Sv (specified) | Zones 1,3 lower EC | Delay (min) | Zones 2,4 upper EC | Delay (min) |
|---|---|---|---|---|---|---|---|---|---|
| 2 | Unoccupied | Heating | No | No | N/A | Clear | 0 | Clear | 0 |
| 2 | Unoccupied | Heating | No | Yes | N/A | Clear | 0 | Clear | 0 |
| 2 | Unoccupied | Heating | Yes | No | N/A | Clear | 0 | Clear | 0 |
| 1 | Unoccupied | Heating | Yes | Yes | N/A | Tint | 0 | Clear | 0 |
| | | | | | | | | | 0 |
| 2 | Unoccupied | Cooling | No | No | N/A | Clear | 0 | Clear | 0 |
| 2 | Unoccupied | Cooling | No | Yes | N/A | Clear | 0 | Clear | 0 |
| 2 | Unoccupied | Cooling | Yes | No | N/A | Clear | 0 | Clear | 0 |
| 1 | Unoccupied | Cooling | Yes | Yes | N/A | Tint | 0 | Tint | 0 |
| | | | | | | | | | 0 |
| 3 | Occupied | C or H | No | No | N/A | Clear | 0 | Clear | 0 |
| 4 | Occupied | C or H | No | Yes | N/A | Clear | 0 | Clear | 0 |
| 5 | Occupied | C or H | Yes | No | N/A | Clear | 0 | Clear | 0 |
| 7 | Occupied | C or H | Yes | Yes | >3000 | Tint | 0 | Tint | 0 |
| 8 | Occupied | C or H | Yes | Yes | <2700 | Tint | 0 | Clear | 10 |
| 6 | Occupied | C or H | Yes | Yes | >1800 | Tint | 0 | Clear | 10 |
| 9 | Occupied | C or H | Yes | Yes | <1600 | Clear | 10 | Clear | 10 |

Note: "Sun up?" indicates daytime hours when the sun is above the horizon.

### *2.4. Interior shades*

A manually-operated, interior, 2.40 m wide by 1.99 m high (7.85 x 6.54 ft), two-zone Venetian blind was installed on each of the two windows (Hunter Douglas Duoflex) to block direct sun or control glare, as required by the occupants. The blind consisted of 2.54 cm (1 in.) wide, matte white, concave down, curved slats where the slats in the upper zone, corresponding in height to the upper window zone, had a different, more open angle from the lower zone slats. The slat angles of the two zones were slaved or dependently linked. The blind could be raised to any height and when fully raised, obstructed the upper vision portion of the EC window by 5.1 cm (2 in.).

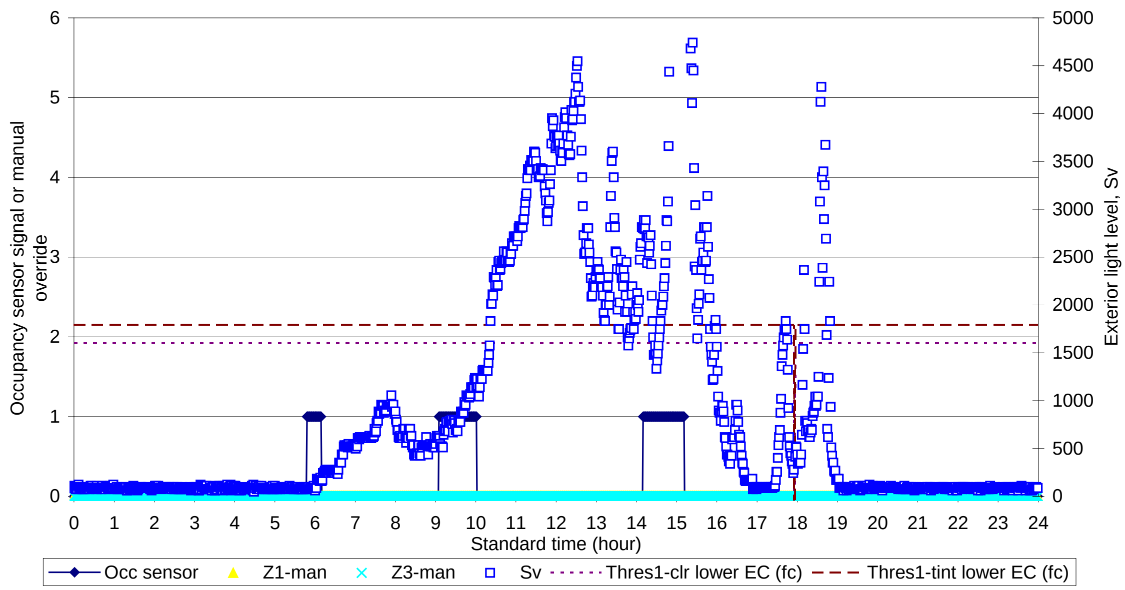
## 3. Assessment of the EC window control system

### *3.1. Diagnostics*

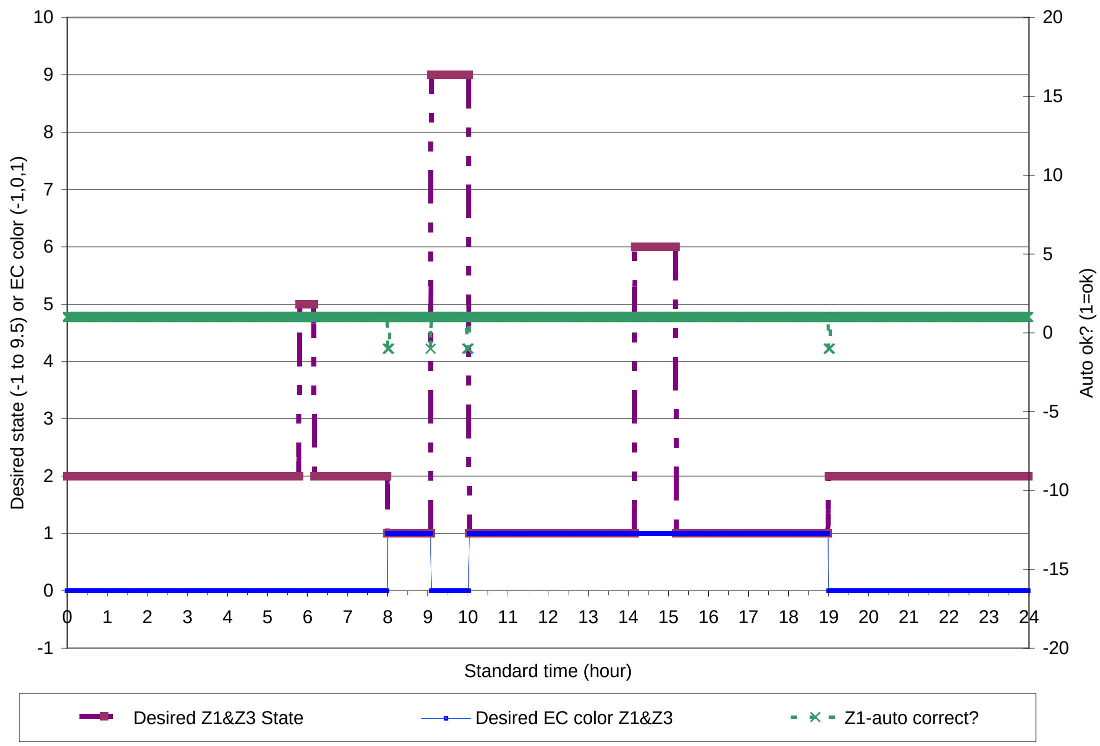
For larger installations, fault detection and diagnostics (FDD) tools are invaluable for troubleshooting operational problems with complex control systems before and during occupancy. This pilot demonstration provided an opportunity to define what data are needed and how these data could be used to detect and diagnose potential programming and implementation errors.

There were two sources of data available for this study. Passive sensors were installed in the room and these data were monitored to independently verify manufacturers' reported data. Data from the manufacturer's control systems included manual overrides for each EC zone, pane status (clear or tinted), the amount of time each pane was in the clear or tinted state, and occupancy sensor status. Data were sampled and recorded via an RS485 network every 1 min over a 24-h day for 15 months from March 15, 2009 to July 1, 2010 using the National Instruments LabVIEW data acquisition system.

For each monitored day, sensor inputs were used to independently determine the automatic state of the EC windows (Figure 2). These computed values were compared to the actual state of controls and queries were made when the two values disagreed. Periods when the automated system was manually overridden were excluded from this analysis. There were a few errors in the data stream that complicated the analysis: a) bad lines of data, and b) erroneous pane status data. The first error was due to noise on the




1) occupancy (1=occupied, 0=not) (left y-axis)
2) manual override of Z1 and Z3 where 1=override, 0=auto, -1=error (left y-axis) (no override for this day)
3) Sv = vertical exterior light level with clear and tint thresholds for lower window zones indicated as dotted lines (right y-axis)




1) Desired control state -- see Table 2 (left y-axis)
2) Desired EC color (0=bleach, 1=tint) (left y-axis)
3) Is control of Z1 and Z3 correct? (1=yes, -1=no,-10=sim or switch error) (right y-axis)

**Fig. 2.** Example graphs of control diagnostics for July 29, 2009.

communications network, which on occasion interrupted data transmission. Days with errors exceeding 20 min over the 24-h day were excluded from analysis, resulting in a 1% loss of the original 15-month dataset. For the second source of error, queries for data from the manufacturer's party line type communications bus were on occasion not answered at the 1-min interval, resulting in loss of pane status data. Actual EC operations were unlikely to have been affected; however, error checking could not be performed without these data. For days when pane status data were not available for more than 20 min for any of the eight panes over the 24-h day, the entire day's data were excluded from analysis. This resulted in a 13% loss of the original 15-month dataset. Clearly, having a clean datastream is essential for facilitating diagnostics: this prototyped networked system would need minor modifications to improve reliability.

Because the manufacturer used a finer time step for control than the acquisition timestep (1/min) to evaluate sky conditions, we were unable to independently determine the exact same sensor values used for control. This resulted in a minor number of incorrect assessments of control error. Additional diagnostic checks were made. Pane status data were checked to determine if the two panes for each zone were both at the same switched state when in the automatic control mode (one controller was used to control two EC panes): no errors occurred. No errors in manual or automated switch actuation were logged by the manufacturer over the monitored period. Between these and other potentially unidentified sources of error, there was on average 8-12 min/day between the four controlled EC zones when the automated control system was either not working properly or we were unable to independently assess its performance. For days when automatic control errors exceeded 30 min/day, the entire day's data were excluded from analysis. This resulted in a 3% loss of the original 15-month dataset.

As an independent check against the manufacturer's reported data, the transmittance of an upper and lower EC window pane were monitored at 1-min intervals to determine whether the EC windows actually operated as intended. A Li-Cor photometric sensor (LI-210SA, ±1.5%) was mounted against the inside vertical surface of the window glazing 11.4 cm (4.5 in.) from the frame edge. The ratio, t, of this interior illuminance and the exterior light level, Sv, was used to judge the switching status of the window pane. If exterior light levels were sufficiently bright just past sunrise or before sunset ($Sv>500$), the pane status was tinted, and $t<0.15$, then the actual tint level was judged to agree with the manufacturer's pane status data (colored state). For the lower and upper panes, the measured data agreed with the reported pane status data on average 98% and 95% of the time when tinted, respectively. The pane status data were judged to be reliable over the 15-month monitored period.

Three errors in the EC control system were detected as a result of running these diagnostics: 1) the EC window control system did not consistently return to the automatic mode after being manually overridden by the occupant, 2) the EC window did not always respond to a command from the automated system, and 3) the control system did not consistently log the 10-h time limit leading to the EC window being tinted for greater than 10 h. The infrequent, sporadic nature of the first two errors made it difficult to detect and diagnose: these two *software* errors (the manual override switches were operating correctly) were analyzed and the system was fixed December 11, 2009, thereafter operated without errors. The third error appeared to have been fixed in August 2009, but then reoccurred from March 2010 through the end of the monitoring period. Pane status data were determined to be an accurate indicator of actual EC operations whereas the control system timer data were found to be faulty. Since this error was minor, occurred after 19:00 LT, and did not appear to inconvenience the end users (see Section 4.1), data were retained. Statistics for this third error are given in Table 3. For example, pane status data indicated that the lower windows were tinted for more than the 10 h limit on 10 days out of the total 204 day monitored period, whereas the control system timer indicated that there were 75 days when this limit was exceeded. This error resulted in the upper and lower windows being tinted for more than the 10 h limit for a total of 122 min and 283 min, respectively, over the monitored period.

The manufacturer should be credited for quickly developing a control system within tight time constraints at the initial launch of the project. Analysis of the data was performed over the solstice-to-solstice period between December 11, 2009 to July 1, 2010. Of the 202 days within this six-month period, 145 days (72%) were retained for the analysis using the filters described above with a total of 90 days when the rooms were occupied.

**Table 3. Length of time EC tinted state exceeded the 10-h limit based on pane status and control system timer**

| | Based on control timer | Based on pane status | | |
|---|---|---|---|---|
| | Total (days) | total (days) | total (min) | avg (min) |
| Number of days in monitored period | 204 | 204 | | |
| Number of days and total time when 10-h tint limit was exceeded | | | | |
| Zone 1 or 3: lower windows | 75 | 10 | 283 | 28.3 |
| Zone 2 or 4: upper windows | 35 | 4 | 122 | 30.5 |

Testing the manufacturer's executable control module under all boundary conditions in a software environment is the most efficient method of checking for programming errors. For pilot demonstrations of emerging technologies, one can independently replicate the logic of the control system to detect programming, installation, and operational errors during actual operations and use these data to analyze system performance. To implement this latter solution, the bid specification would need to require that control inputs and sensor data, setpoints, device status and control modes, and manual switch actions be available to the control system via a reliable communications network. In this demonstration, the lighting system provided occupancy data to the EC control system, requiring an *integrated* communications network and cooperation amongst different vendors. Graphical displays and archiving of data (features typically provided by the manufacturer) would facilitate diagnosis of intermittent errors, such as the ones detected in this analysis.

The most significant barrier to routine implementation of such a scheme is the independent replication of control logic. This requires that the commissioning agent know the exact details of the control algorithm and more often than not, this information is proprietary. Instead, one could incorporate and test the manufacturer's black-box executables within the fault detection and diagnostics (FDD) module of the energy management control system (EMCS). Separately, most applications will not tolerate or cannot afford installation of a secondary network of monitoring sensors. Independent verification of clear or tint activity could occur using spot measurements over limited periods and monitoring of control system operations, if possible, in parallel. A post-occupancy measurement and verification phase should be included in the bid specifications.

Fine-tuning the control system to occupant preferences is significantly more challenging. With this system, the facility manager would need to have access to the control setpoints for each zone and would need to work with the occupants iteratively to arrive at acceptable setpoint levels (e.g., threshold setpoints for direct sun and glare). Self-tuning, learning control algorithms would likely yield more efficient, acceptable operations. Manual switch data given in Section 4.1 provides some insights into the challenges of this problem.

### *3.2. Threshold values*

Separate threshold values were defined for the upper and lower EC window zones to trigger tinting of the windows (Table 1). For the upper zone, the intent was to tint the windows when there was direct sun in the plane of the window. For the lower zone windows which were more directly within the occupants' field of view, the windows were tinted to minimize discomfort glare from either direct sun or bright sky conditions and cleared in the absence of glare to admit daylight. The threshold value for tinting the lower zone was less than that of the upper zone, enabling the upper zone to admit more daylight. Deadbands for switching the tinted EC window back to the clear state were defined by 90% of the threshold values. When implemented in code, the selected values were matched to the closest 8-bit value (e.g., Sv = 3000 nominal; Sv = 3007 8-bit value): in this discussion, we will refer to the more precise 8-bit threshold values.

Vertical illuminance is a poor man's proxy for determining when the sun orb is not being obscured by clouds and is also in the plane of the window. The value can be indicative of either very bright, diffuse cloudy sky conditions or a very clear blue sky with the solar disk in the field of view. The measure can be confounded by variations in reflected light off the ground and surrounding buildings. In prior research, a vertical exterior illuminance threshold between direct sun and no sun was set at 30,000 lux (2788 fc) based on field observations, where vertical illuminance was measured with a research-grade, color-corrected, cosine-corrected illuminance sensor. For this installation, a commercial light level sensor was used: its white diffusing dome affected spatial and spectral response. Figure 3 illustrates how response varied over a period of a month on clear sunny days. Both types of sensors exhibited variable response on a partly cloudy day. Inconsistency in the control sensor response to actual outdoor illuminance conditions led to an inconsistent response on the part of the control system.

This is further illustrated in Figure 4. On a clear sunny day (April 1, 2010), the light level sensor signal, Sv, increased rapidly once the sun came into the plane of the window and a clean profile of the monitored light level indicated that sky conditions were clear. The transition between diffuse and direct sun conditions occurred at around 13:40 ST when the sun came into the plane of the west-facing window. Sv levels were around 2000 to 4000, within the selected threshold level for tinting of the upper windows of 3007 for direct sun control. Under partly cloudy or overcast sky conditions (March 25, 2010), this threshold level was reached in the *morning* hours (11:45 ST) prior to the sun being in the plane of the window. As a result, the upper EC windows tinted in the morning – more as a response to the bright surroundings and sky conditions than the presence of direct sun.

For discomfort glare and daylight control, a global light level measurement cannot capture the spatially-complex luminance distributions produced by local site conditions, such as exterior obstructions from neighboring buildings, reflectances of ground and surrounding surfaces, and variable solar and sky conditions. View angle, task, and sensitivity of end users to discomfort glare also determine whether the selected threshold values will lead to a satisfactory indoor environment. Deriving control algorithms that address end user comfort and environmental quality (view, brightness perception, etc.) is perhaps the most significant challenge for developers of automated façade control systems.

Given this complexity, the occupants' actions – manual overrides of the automated EC control system, use of the interior blinds – were analyzed to determine whether the lower window's threshold value for glare was adequate (see Section 4). Discomfort glare was also computed using a simple subjective rating (SR) system, which is based on the vertical illuminance at the eye [10]. Measurements were in fact taken at the indoor surface of the two EC panes to avoid disturbing the occupants, which represents the worst case position for discomfort glare, not that experienced by occupants in the room. These data were used to analyze the manual switch data.

There were some concerns that a conservatively low threshold level would lead to the EC windows being tinted throughout most of the year. If all four zones were frequently tinted when occupied, the interior environment could be gloomy given that the visible transmittance of the tinted windows is very low (center of glass Tv = 0.03). Of the average 191 min/day that the room was occupied over the six-month period, the upper and lower EC windows were tinted 57 min and 87 min on average, or 30% and 45% of the average occupied period, respectively (Table 4). On an infrequent basis, the occupants overrode the automated EC window control system to increase daylight levels: this is discussed in Section 4.

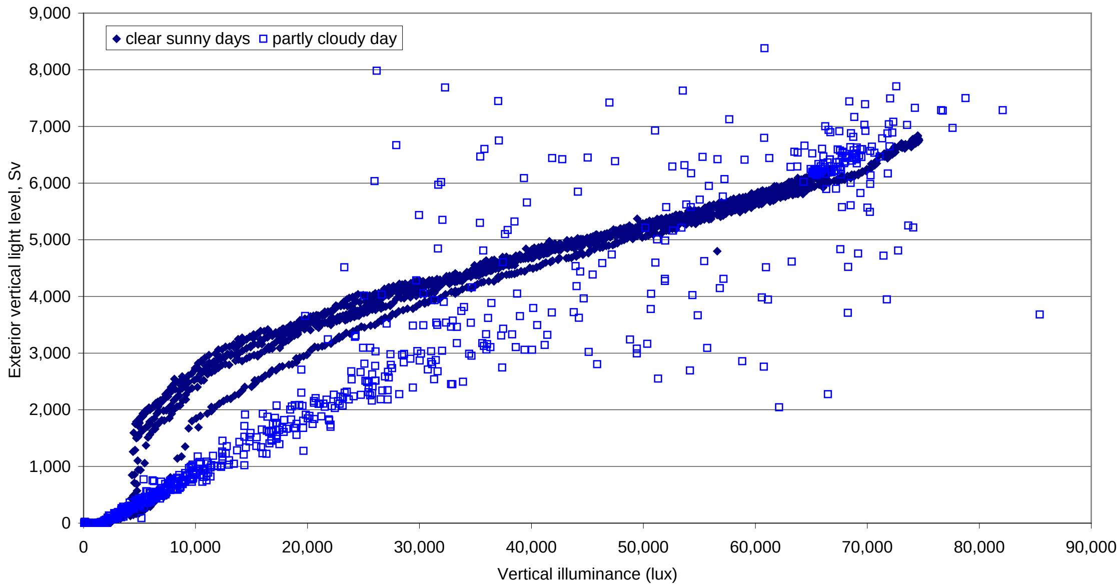



**Fig. 3.** Relationship of exterior vertical illuminance to exterior vertical light level, Sv, measured by the commercial sensor. Data are given for clear sunny days (September 4, 6, 7, 8, and 20, 2009) and one partly cloudy day (September 5, 2009). Note the variation in output as solar angles change on clear sunny days over the course of the month.

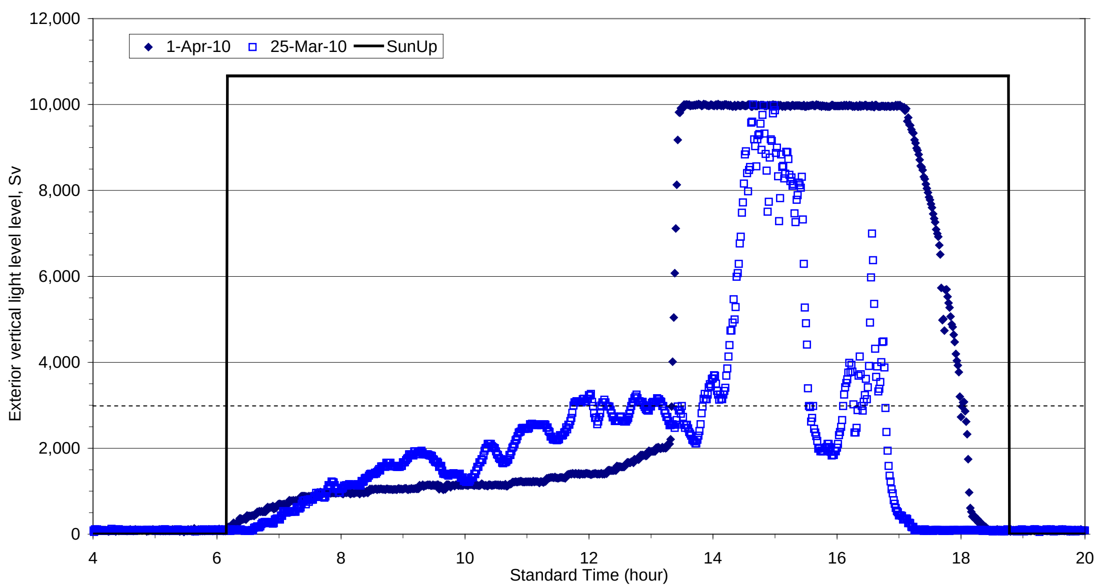



**Fig. 4.** Exterior vertical light level, Sv, on a sunny (April 1, 2010) and partly sunny (March 25, 2010) day. A positive “sun up” value indicates the time when the sun is above the horizon.

**Table 4. Length of time EC in tinted state**
Period: December 11, 2009 to July 2, 2010 (204 days)

| Unoccupied days (min/24-h day) | | total | | |
|---|---|---|---|---|
| Zone 1 or 3: lower windows | Summer | 600 | | |
| Zone 2 or 4: upper windows | Summer | 600 | | |
| Zone 1 or 3: lower windows | Winter | 600 | | |
| Zone 2 or 4: upper windows | Winter | 0 | | |
| **Occupied days (min/24-h day)** | **avg** | **stdev** | **max** | **min** |
| Total min/day tinted on occupied day | | | | |
| Zone 1 or 3: lower windows | 500 | 101 | 646 | 266 |
| Zone 2 or 4: upper windows | 203 | 236 | 650 | 0 |
| Min/day tinted during occupied periods | | | | |
| Zone 1 or 3: lower windows | 87 | 68 | 263 | 2 |
| Zone 2 or 4: upper windows | 57 | 54 | 231 | 0 |
| Min/day room was occupied | 191 | 100 | 397 | 13 |

### *3.3. EC switching speed*

The switching speed of the EC windows decreases with lower levels of incident solar radiation and outdoor temperatures and if too slow, can lead to occupant discomfort and annoyance particularly if discomfort is acute – for example, visual discomfort due to direct sun under partly cloudy conditions. Switching speed was determined using the monitored transmittance of the window, t, approximated by the ratio of the interior vertical illuminance at the glass to the exterior vertical light level, Sv. On a cold partly sunny winter day (December 21, 2009, 9:00 ST, Tdbt = 0°C (32°F), Figure 5) when Sv = 1164 and the EC was switched to tinted, the transmittance of the lower EC window decreased from 0.37 to 0.26 (5 min), 0.13 (10 min), 0.08 (15 min), and 0.05 (20 min). After 43 min, t decreased to 0.02. On sunny and/or warm days, the lower EC window switched in about half the time (10 min). The large-area window (1.32 $m^2$, 14.3 $ft^2$) had a bus bar distance of 0.63 m (2.07 ft).

Interior shade usage was not monitored on a detailed basis. Observations of shade position every two weeks indicated that the shades were not being used to control direct sun and counter slow switching speeds. Occupants may have attempted to speed up EC switching using the manual override switches in the room. This is discussed in Section 4.

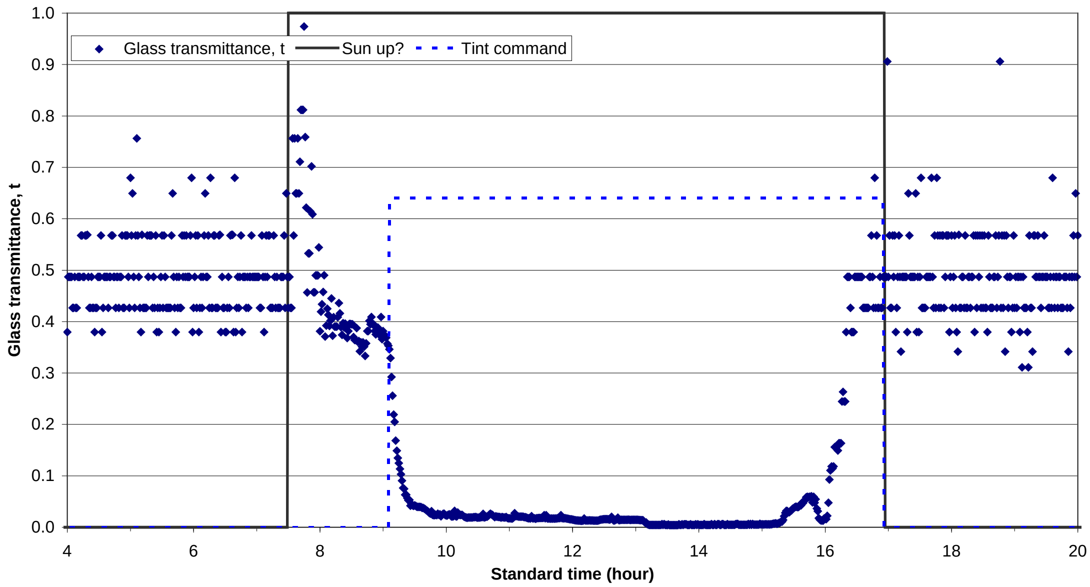



**Fig. 5.** Measured "t" ratio of interior vertical illuminance to exterior vertical light level, Sv, on a cold, partly sunny day (December 21, 2009). A positive "sun up" value indicates the time when the sun is above the horizon.

## 4. Occupant interventions

### *4.1. Manual override of the automated EC control system*

With a fully-monitored outdoor testbed, one has the luxury of assessing performance by making detailed measurements using a broad network of instruments. Under occupied conditions, however, one has the unique opportunity to evaluate performance by making observations of occupant interactions with the interior environment and controls. In this case, occupants modified their environment by either overriding the automated EC control system by using the manual switches or adjusting the window blinds. While manual override of automated controls is not a definitive measure of user satisfaction with the automated controls, they should be correlated. End users that do not or rarely override the automatic controls are likely to be more satisfied than those that frequently override the system. When the system is overridden, it is also instructive to understand why and how the windows were overridden. No subjective survey data were obtained. Observations made in this study are limited to a single conference room and are therefore only indicative of potential performance.

We first explain the use of the room. Typical conference room use was said to be primarily face-to-face conversations with possible use of individual laptops. The single rectangular table seated eight people. Additional chairs were arrayed against the back wall for up to an additional eight people. A flat-panel, low reflectance, large-area LCD screen was mounted on the south wall some time after the EC windows were installed. Prior to this, meetings that used audio-visual projections were said to be rare. Exterior west-facing views were pleasant: the Washington Monument was visible through the right-hand window.

Occupants had the option of altering their ambient electric light level, EC window tint level, interior Venetian blind height and tilt angle, and supplementing the ceiling-delivered space conditioning with additional heating and air-conditioning from a convector unit installed below the window. Data on when and how the automated EC control system was manually overridden were logged on a 1-min basis. Lighting energy use was also monitored independently but data on the occupants' selection of light level on the keypad were not made available. Use of the interior shades was observed once every two weeks (monitoring instruments and time-lapsed video were not permitted). HVAC operations and use were not logged.

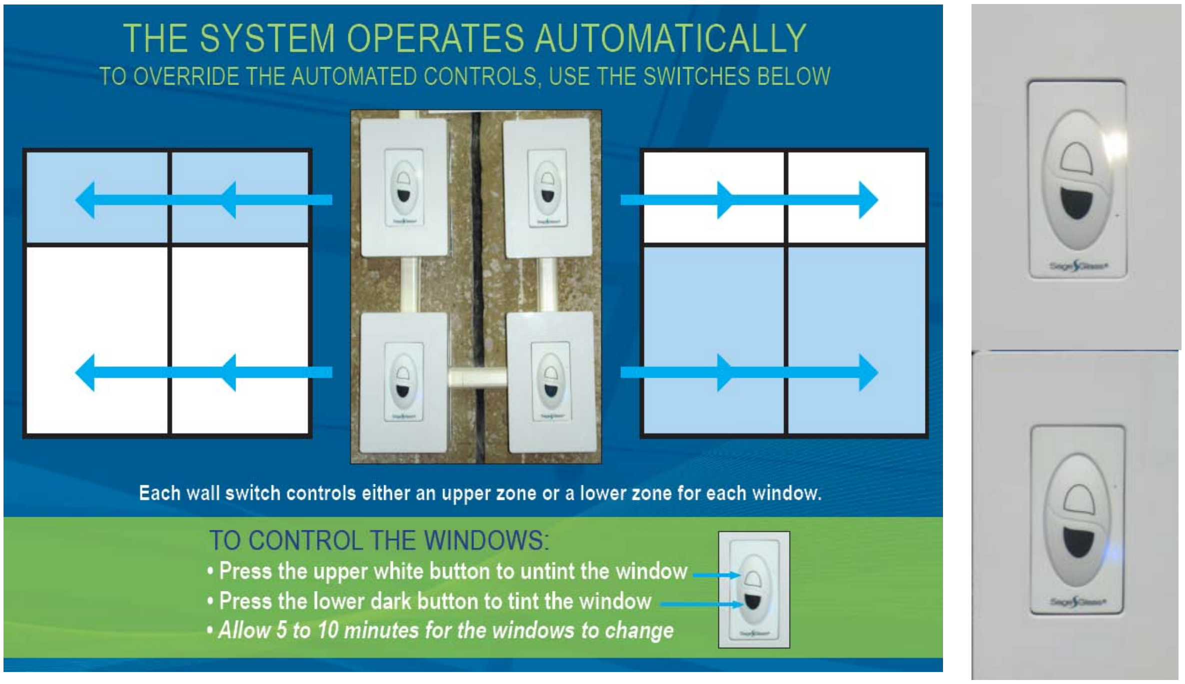



**Fig. 6.** Left: Signage instructing occupants on how to switch the windows (above). Right: The color of the LEDs indicate whether the windows are in the clear (white switch above) or tinted (blue switch below) state.

It was imperative that occupants understood how to operate the manual switches. The switches themselves seemed to be fairly self-explanatory. For each of the four window zones, the user could push either the top white button or the lower dark button to switch a window zone to the clear or tinted states, respectively. At all times, a white or blue LED next to the white or dark button was lit to indicate which state (clear or tinted) the window zone was in. However, the LED did not blink when the EC window was in the process of switching between states. To make doubly sure that there was no confusion, a very large sign with images and text was installed at the switches to explain how to override the automatic system, which switch corresponded to which window zone, what the switch did, and that the override would take 5-10 min to change the windows (Figure 6). Diagnostics (Section 3) indicated that the manual override switches worked as designed during this six-month monitored period.

As with any new technology, there are a number of unanticipated ways a person can interact with the user interface. Some simply push buttons to see what happens. Others avoid using the interface for fear of causing the system to fail. If the occupant is unable to figure out or understand how the interface works, frustration and annoyance can result, leading to complaints or the occupant simply giving up and being uncomfortable. For this particular installation, it is unlikely that the end users would have simply given up and not used the switches due to lack of understanding on how the switches worked or put up with uncomfortable conditions. The conference room could only be used by a specific group and these end users were very proactive and vocal. The project team members were also on site frequently, had explained use of the interface initially, and were available if any further clarifications were needed. The end users also had interior Venetian blinds at their disposal, which could be used to reduce discomfort from the window. The blinds were used occasionally, as discussed in Section 4.2. While the signage and ready access to project staff is not typical of what would occur in the real world, for this study, it helped to focus analysis on whether the EC window technology and its control algorithm were adequate, rather than the design of the user interface.

Table 5 provides some statistics on how often the manual switches were used and for which zones. To obtain a clear assessment, we first eliminated the initial period just after the EC windows were installed and made operational and the period when the controls were not operating reliably (the automatic controls were overridden two times as frequently during the initial period compared to afterwards when the controls were working properly). The analyzed period encompassed the last six-month, solstice-to-solstice period.

Occurrences where the manual overrides were made for demonstration purposes were also eliminated. The room was occupied on average four times per day for a total of 3.2 h/day. Over the six-month monitored period and on work days when the room was occupied (N = 90), the average number of times automated control of any of the four window zones was manually overridden was 0.02-0.13 times per 24-h day with a maximum of one time per day. For all days when the room was occupied, the automated controls were overridden for an average of 7-18 min or 3-6% of the total occupied period per day.

There were a total of 328 meetings that occurred in the room over the monitored period, each lasting at least 10 min. Of these, there were a total of 24 meetings when the automated controls were overridden, 10 of which were overridden for demonstration purposes, leaving 14 out of 328 (4%) meetings held during the six-month period when the automatic system was manually overridden.

*Demonstration mode*

Twenty-four of the 67 manual overrides for the four windows (36%) occurred in a manner that suggested that the occupants were demonstrating the switching capabilities of the EC windows to visitors. Seven of these occurred within 4-7 min before the end of the meeting. Another seven occurred within the first 6 min of a single meeting, where the EC windows were switched to opposite states when first entering, then a minute later again, then after 5 min was set to a final state which was used for the remainder of the 1.5-h meeting. Eight were made in a 20-min meeting: all four zones were switched upon entering and then four opposite commands were issued 16 min later. The remaining two overrides were made at nighttime (20:00 ST) to a tinted state when the room was occupied for a total of 4 min.

*Overrides made in the first 5-min upon entry*

The lower portion of Table 6 shows under what conditions the manual switches were activated to override automatic control, excluding those made for demonstration purposes. If one looks at how the individual window zones were overridden, one notices that of the total number of overrides, 28 out of the total 43 (65%) were made within the first 5 min of entering the room and 14 of these were made to the same state as the automatic mode of control.

*Override to the same state as the automatic mode*

Of the total 43 overrides in this six-month period, 16 (37%) were made to put the EC windows into a state they were already in; e.g., the occupant pushed the tint button even though the windows were already tinted or in the process of tinting. Automated control status was indicated by the manual switch LEDs within 2-3 s of the change in occupancy: this was verified in the field. Automated control was initiated 10 s after entry to avoid false triggers. It is unlikely that the occupants were confused by the LED status lights. More likely, the occupants were proactively setting the EC windows to a state they knew they wanted as soon as they entered the room, anticipating and countermanding the automatic controls given prior experience with the automated system. Regular users likely knew by prior experience that the manual override would remain in effect until the end of the meeting.

There were more commands to make the windows clear (13 times, 30%) than tinted (3 times, 7%) when already in this state. Fourteen of the 16 overrides to the same state were made within a minute of having entered the room. One explanation may be that occupants were reacting to perceptions of the room's lighting quality. On three occasions, a prior meeting had occurred 15-31 min prior to start of the next meeting and due to the cold, partly sunny, afternoon winter conditions, the upper zone ECs were still in the process of switching to the clear, unoccupied control state when occupants entered the room (Tv = 0.12, 0.22, 0.18, respectively instead of Tv = 0.40 for the clear state). Occupants may have been simply reacting to the room's dim daylit environment: on two of these days, the ECs were overridden to clear. In the summer between 9:00-19:00 LT, all windows were tinted in the unoccupied state to control solar heat gains, so upon entry to the room, overrides to clear were likely made as a reaction to the room's dim interior. An occupant's perception of gloom or dim lighting levels would be dependent on whether they had been working previously in a space with the existing windows (Tv = 0.36) or in the windowless open plan office space. The majority of occupants using the conference room had private perimeter offices with windows.

**Table 5. Frequency of manual overrides when occupied**
Period: December 11, 2009 to July 2, 2010

| | | avg | stdev | max | min |
|---|---|---|---|---|---|
| Number of occupied periods* per 24-h day | | 4 | 2 | 8 | 1 |
| Number of minutes room was occupied (in 24-h day) | | 191 | 100 | 397 | 13 |
| Percent of 24-h day when room was occupied | | 13% | 7% | 28% | 1% |
| Number of times automated control was overridden in a 24-h day over total monitored period | | | | | |
| Zone 1: lower left window | to clear | 0.07 | 0.26 | 1 | 0 |
| | to tinted | 0.05 | 0.21 | 1 | 0 |
| Zone 2: upper left window | to clear | 0.08 | 0.28 | 1 | 0 |
| | to tinted | 0.03 | 0.18 | 1 | 0 |
| Zone 3: lower right window | to clear | 0.07 | 0.26 | 1 | 0 |
| | to tinted | 0.02 | 0.15 | 1 | 0 |
| Zone 4: upper right window | to clear | 0.13 | 0.34 | 1 | 0 |
| | to tinted | 0.05 | 0.21 | 1 | 0 |
| Number of minutes EC window control was overridden in a 24-h day | | | | | |
| Zone 1: lower left window | | 7 | 27 | 164 | 0 |
| Zone 2: upper left window | | 8 | 24 | 140 | 0 |
| Zone 3: lower right window | | 7 | 27 | 163 | 0 |
| Zone 4: upper right window | | 18 | 50 | 304 | 0 |
| Average percent of total occupied period each day when automated EC control was manually overridden | | | | | |
| | N (days) | | | | |
| Zone 1: lower left window | 90 | 3% | 9% | 49% | 0% |
| Zone 2: upper left window | 90 | 3% | 9% | 45% | 0% |
| Zone 3: lower right window | 90 | 3% | 9% | 49% | 0% |
| Zone 4: upper right window | 90 | 6% | 17% | 78% | 0% |

| | |
|---|---|
| Z2 | Z4 |
| Z1 | Z3 |

Window zone numbering convention as seen from the interior

**Table 6. Mode of manual overrides for the 24 meetings**

Period: December 11, 2009 to July 2, 2010

| | | |
|---|---|---|
| Total number of meetings | 328 | |
| Total number of meetings with manual override | 24 | 7% |
| Total number of meetings with manual override excluding demonstration modes | 14 | 4% |

| | | Lwr, L Z1 | Upr, L Z2 | Lwr, R Z3 | Upr, R Z4 | Total | % of total |
|---|---|---|---|---|---|---|---|
| Total number of overrides | | 14 | 19 | 12 | 22 | 67 | – |
| Total number of overrides excluding demonstration modes | | 10 | 10 | 8 | 15 | 43 | – |
| Percentage of total manual overrides without demo mode | | 23% | 23% | 19% | 35% | 100% | – |
| User manually overrides automatic control to do the following (number of overrides, excludes demonstration mode overrides): | | | | | | | |
| Tint | all cases | 4 | 3 | 2 | 4 | 13 | 30% |
| Clear | all cases | 6 | 7 | 6 | 11 | 30 | 70% |
| Tint or Clear | when first enters the room (<5 min) | 6 | 6 | 4 | 12 | 28 | 65% |
| Tint | but already tinted | 2 | 0 | 0 | 1 | 3 | 7% |
| Clear | but already clear | 1 | 3 | 2 | 7 | 13 | 30% |
| Tint or Clear | when first enters room (≤ 1 min) but overrides to same state as automated control | | | | | 14 | 33% |
| Tint | but Sv<T (to control glare) | 0 | 1 | 0 | 1 | 2 | 5% |
| Clear | but Sv>T (to admit more daylight) | 4 | 3 | 3 | 1 | 11 | 26% |
| Tint | but durability limit in effect before 9:00 | 0 | 0 | 0 | 0 | 0 | 0% |
| Tint | but durability limit in effect after 19:00 | 0 | 0 | 0 | 0 | 0 | 0% |

Notes: Lwr: Lower; Upr: Upper, L: left; R: right EC zone; S<T: exterior light level (Iv) signal less than threshold, T.

It seems unlikely that the manual overrides were made because the occupants thought the slow-switching ECs were not changing to their desired state. For lighting, one sees the light level change as soon as one touches the switch. For thermostat control of the heating or cooling system, the response time is comparatively slow and people will wait for comfort conditions to be achieved. After nine months of experiencing this technology, the primary occupants who frequently used this room had most likely come to understand how fast the windows switched. The manual override data are given for six months following this nine month period. If the occupant already knew that the windows switching speed was slow but still manually overrode the windows, it is likely that they were not manually overriding the controls to speed up the switching. End users might have anticipated or looked at the LED indicator for automated control, then proactively switched the windows manually to keep the windows at a specific state.

For example, they might have entered the room with the intent of using the AV equipment and didn't want the windows to clear in the middle of their presentation.

On only one occasion, the occupants repeated the same command within one minute of first pushing the button (20 h at night). One would have expected more repeated commands, particularly during the winter, if occupants tired of waiting for the EC windows to switch (similar to those waiting for an elevator who push the button multiple times) or would have immediately lowered the shade. Unless the occupants or other staff repositioned the blinds every day, it appears that neither of these actions occurred: the blinds stayed in the same position for periods of months. In one case (June 28, 2010), the EC windows were switched to tinted when glare conditions were severe: transmittance of the four windows were decreased to Tv = 0.03 in 10-15 min (solar incident angle = 50º, Sv = 2292) and shades were still not lowered.

*Reasons for override: daylight/glare*

There could be any number of reasons why the automatic control system was overridden: visual or thermal discomfort; desire for daylight, view, or privacy. Below are some possible explanations that could be inferred from the monitored data upon detailed analysis of individual switch actions.

Of the total number of overrides, 11 overrides (26%) were made to *clear* when the exterior light level, Sv, was greater than the threshold for direct sun and glare control, indicating that perhaps the occupants desired more daylight. Seven of the 11 overrides were made to the lower EC windows.

Irrespective of Sv, four were made on a clear sunny day (June 28, 2010) where the occupants switched the four tinted unshaded windows to clear (Sv = 98), then when glare discomfort levels were well over "just intolerable" levels 20 min later (Sv = 2292), the occupants switched all four windows back to tinted. Once overridden, the control system returned to automatic after the occupants had left the room for 2 min, so in this case when conditions became uncomfortable, occupants had to use the manual switches to remedy the situation. Another two overrides were made in the same way (March 19, 2010) with occupants first switching all windows to clear (Sv = 2558), then manually switching them back to tinted 45 min later when the sun transitioned into the plane of the window (Sv = 9734).

On four separate meetings (February 18, 19, 24, 2010 and March 26, 2010; Sv = 5298, 2631, 2437, 1952, respectively, threshold to tint = 3007), occupants switched only *one* of the two upper zones to clear with the remaining zones left in the tinted automatic mode: this would have increased the brightness and daylight levels in the space. In both instances, the interior shade was lowered over the upper window zones, which would likely have controlled direct source glare and diminished the luminance contrast between the lower tinted zones and the upper clear zones. This mode of control with an interior blind to control direct sun was implemented automatically in a prior field test [4] to improve daylight levels while controlling for direct sun and glare, but with EC controls that allowed for continuous modulation of EC tint in each of the upper and lower zones. In this installation, the EC windows could only be switched to fully clear or fully tinted so occupants had to judge beforehand how to switch the ECs.

*Manual override and threshold value*

There was only one instance to assess the threshold value used to switch from clear to tint to control direct sun and glare. In this instance, the ECs were overridden from a manual mode of clear to tint in the middle of a meeting when the interior Venetian blind was completely raised. The override occurred under partly sunny conditions when Sv = 2292. Direct sun extended 0.67 m (2.2 ft) into the room at the 0.76 m (2.5 ft) workplane height (surface solar azimuth = 5º, profile angle = 49º). Discomfort glare was at the level of 3.05-3.12 ("intolerable glare") if the eye was positioned at the worst-case position at the surface of the EC window (in direct sun). This Sv value is between the two threshold values that were selected for the upper and lower zones, 3007 and 1794 respectively, but sky conditions were rapidly changing: the Sv value increased from 2292 to 10,000 within 12 min after the manual override was made.

There was also only one instance to assess the threshold value used to switch from tint to clear to enhance daylight (April 27, 2010, 11:52 LT, no direct sun). In this instance, the lower EC zones were tinted and the upper were clear when in automatic mode for 86 min after the start of the 132-min meeting. All EC windows were switched to clear when Sv = 2292 (coincidentally the same value in the prior paragraph). Sky conditions were fairly stable (standard deviation = 364 over 5 min period before and after the time of the override). The upper window zones were covered by the interior Venetian blind with a partially-open slat angle on the right-hand blind and nearly closed angle on the left-hand blind. Assessments of the threshold value for other manual overrides to clear were confounded since the occupants switched only one of the two upper zones to clear, as discussed above.

*Durability tint limit*

As mentioned in Section 2.2, the EC windows were switched automatically to clear at the end of the day if the 10-h tint limit was exceeded. The primary concern was that occupants would want the EC windows tinted during lockout periods. Since there was no user feedback indicating why the windows would not tint, end users may have concluded that the control system was not working properly. Manual switch actions were logged prior to and after the 9:00-19:00 LT lock-out period to determine if any one tried to switch the windows to tint. Monitored data showed that no manual switch actions were logged when the durability limit was in effect either from the previous day (before 9:00 LT) or after 19:00 LT, indicating that for this application the 10-h limit imposed no restriction on user operation of the EC windows (Table 6).

*4.2. Manual use of interior Venetian blinds*

Use of the interior shades is another indication of satisfaction with the environmental conditions. The two-zone, white interior Venetian blinds are described in Section 2.4. Occupants could raise and lower the blind and change the slat angle as with any conventional interior blind. The west orientation is difficult to shade without loss of view and daylight. Results of a prior subjective study for a south-facing private office indicated that shades were required with EC windows in order to reduce visual discomfort due to sunlight and bright skies [5].

Based on two-week periodic observations, shade use in this west-facing conference room was as follows (assuming no adjustments between these two-week observations):

– Between October 2009 and December 11, 2009, the shades were fully raised.

– Between December 18, 2009 and March 15, 2009, the shades were lowered over the upper EC windows with a -70° closed tilt angle on the right window and a +45° tilt angle on the left window, where a positive angle is measured down from horizontal enabling a view of the ground from the room interior.

– Between March 26, 2010 and April 23, 2010, the shades were lowered 5-10 cm (2-4 in.) over the top of the lower EC window zones with the same tilt angle in the upper blind zone as in the prior period. The tilt angle in the lower blind zone was fairly closed because the blind was not lowered enough to allow space between the slats.

– Between May 7, 2010 and July 2, 2010, the shades were fully raised.

Note that at no time during the monitored period was view in the lower window obstructed by the interior shade. Given the difficult western exposure, we were expecting that occupants would have fully lowered the shade, but the building across the street obstructed low altitude, late afternoon direct sun. If the blinds were being used to block direct sun, the seasonal pattern of use did not correlate with the variations in solar position.

Non-use of the blinds in the lower aperture seemed to indicate that either discomfort glare was not significant or that occupants were willing to tolerate glare for an unobstructed view out. Use of blinds in the upper aperture during the winter solstice to equinox period may have been to control direct source glare from the sky since the EC tended to be in a clear state during this period or to soften the luminance contrast between the upper clear and lower tinted zones. The selected tilt angles of the slats seemed to be arbitrary. The left blind slats were positioned to a +45° angle which completely obscures one's view of the sky. The right blind slats were positioned to a -70° angle which was also nearly closed or would enable occupants to have a partial direct view of the sky.

## 5. Indoor environmental quality

### *5.1. Window surface temperatures*

If the temperature difference between the indoor window surface and the indoor ambient air can be minimized, thermal comfort can be improved under both cold nighttime conditions and hot sunny conditions. In some cases, one can eliminate the need for perimeter heating and cooling.

*Simulated results*

EnergyPlus [11] simulations were used to compare indoor glass surface temperatures of the old, existing windows and the new advanced EC windows over the year. The modeled windows and room were the same as that of the actual conditions (see Section 6.2 for a full description). Hourly data spanning the year were filtered based on three different environmental conditions: a) cold, cloudy, b) cold, sunny, and c) hot, sunny. Only daytime work hours were included.

During daytime work hours when outdoor conditions were cold and cloudy, the indoor EC glass surface temperature (surface #4) in the clear or tinted state was found to be an average of 13-14°C (23-25°F) warmer than the indoor glass surface temperature of the existing window. The average indoor surface temperature of the existing window was 2°C (36°F) under these conditions while the average indoor surface temperature of the EC window was 15-16°C (59-61°F) (Figure 7a). The ambient room air temperature was 21°C (70°F). Cold, cloudy outdoor conditions were defined by all hours in the year when the outdoor dry-bulb temperature was less than 0°C (32°F) and the exterior vertical irradiance level, Ev, was less than 300 W/m$^2$. Ev values in this range denoted conditions during early morning and early afternoon hours on clear days or cloudy days for this west-facing orientation. Summary data are given in Table 7.

During daytime work hours when outdoor conditions were cold and sunny, the indoor glass temperature of the EC window was 17°C or 12°C (31° F or 22°F) warmer than the existing window for the clear and tinted states, respectively (Figure 7b). The average indoor surface temperature of the existing window was 7°C (44°F) under these conditions while the average indoor surface temperature of the EC window was 24°C and 19°C (75°F and 66°F). Cold, sunny conditions were defined by outdoor temperatures less than 0°C (32°F) and Ev levels greater than 300 W/m$^2$.

In both of these cases when environmental conditions were cold, the warmer indoor surface temperature of the EC window was due largely to the highly-insulated window construction and in part to the solar-optical properties of the EC window pane. The EC glazing in its clear state admitted more solar radiation so the indoor glass temperature was on average 5°C (9°F) warmer than when the EC glazing was in its colored state.

**Table 7. Simulated indoor surface temperature of the existing and EC windows**

| Condition | Hourly data filtered for: | | Vertical Irradiance (W/m$^2$) | Outdoor dry-bulb temperature (°C) | Indoor ambient air temp (°C) | Tglass existing window (°C) | Tglass EC clear window (°C) | Tglass EC tinted window (°C) |
|---|---|---|---|---|---|---|---|---|
| Cold, cloudy | Tout<0°C and | Average | 84 | 21 | -5 | 2 | 16 | 15 |
| | Ev<300 W/m$^2$ | Std.dev. | 57 | 0 | 3 | 3 | 2 | 2 |
| Cold, sunny | Tout<0°C and | Average | 460 | 21 | -3 | 7 | 24 | 19 |
| | Ev>300 W/m$^2$ | Std.dev. | 88 | 1 | 2 | 2 | 3 | 2 |
| Hot, sunny | Tout>20°C and | Average | 622 | 24 | 28 | 34 | 37 | 32 |
| | Ev>500 W/m$^2$ | Std.dev. | 69 | 0 | 4 | 3 | 2 | 1 |

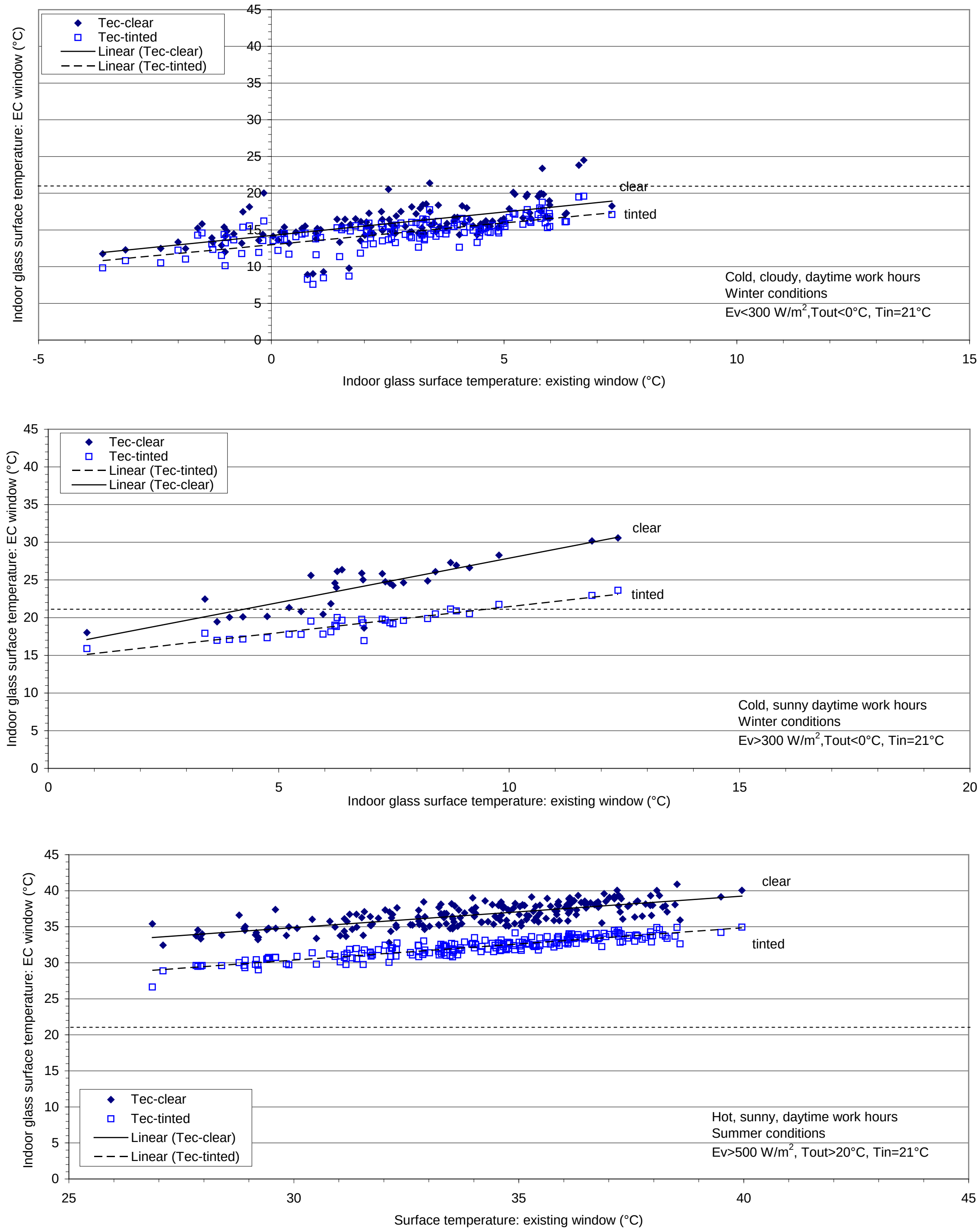



**Fig. 7.** Indoor glass surface temperature of the existing and EC window during daytime work hours when outdoor environmental conditions were a) cold and cloudy (top), b) cold and sunny (middle), and c) hot and sunny (bottom) as determined by EnergyPlus simulations. The horizontal line at 21°C indicates when EC surface temperature is near the ambient air temperature level.

During daytime work hours when outdoor conditions were hot and sunny, the indoor glass surface temperature of the EC window in the clear state was 3±2°C (5±4°F) on average warmer than the existing window but in the tinted state, the EC window was 2±2°C (4±4°F) cooler than the existing window. The average indoor surface temperature of the existing window was 34°C (93°F) under these conditions while the average indoor surface temperature of the EC window was 37°C and 32°C (98°F and 90°F) for the clear and tinted states, respectively (Figure 7c). Hot, sunny conditions were defined in this case by outdoor dry-bulb temperatures greater than 20°C (68°F) and incident vertical irradiance levels greater than 500 W/m$^2$. The ambient room air temperature was 24°C (75°F).

*Measured surface temperatures*

To confirm these EnergyPlus findings, indoor surface temperature measurements were made over a weekend period using epoxy-encapsulated copper thermistors (YSI 44016, ±0.1°C) mounted in the center of the EC glazed unit with heat sink paste and aluminum tape and on the framing with painter's tape. Measurements of the existing window were made in the adjacent space where the exterior exposure was nearly identical. Exterior vertical irradiance data were unavailable. Transmitted vertical irradiance through the window was measured at the indoor face of the glazing (Li-Cor 200, ±5%). The perimeter convector unit was off during these measurements so that no localized cooling of the glass surface occurred during this time.

Under cloudy winter conditions (December 17-21, 2010) when the transmitted irradiance of the existing window was between 0-30 W/m$^2$ and outdoor temperatures were cold, the clear EC glazing was on average 7.8±2.0°C (14.0±3.6°F) warmer than the existing glazing while the EC window frame was 3.8±0.7°C (6.8±1.3°F) warmer than the existing window frame. Measured glass temperature differences were approximately 4-5°C (7.2-9.0°F) lower than the temperature difference predicted by EnergyPlus, explained possibly by differences in interior and exterior environmental conditions between the simulations and measurements.

Under sunny summer conditions (August 6-9, 2010) when the transmitted irradiance of the existing window was greater than 30 W/m$^2$, the indoor surface of the tinted EC window was on average 13.9±3.9°C (25.0±7.1°F) cooler than the existing window while the EC window frame was 8.3±1.7°C (14.9±3.1°F) cooler than the existing window frame. The average measured indoor glass temperature difference (13.9°C, 25°F) was significantly greater than that predicted by EnergyPlus (2°C, 3.6°F), again possibly explained by the differences in environmental conditions; solar irradiance is known to skew the thermistor readings and could be another source of error.

Time-series plots of the surface temperature measurements are given in Figures 8-9. Transmitted irradiance was reduced from 120 W/m$^2$ to almost zero levels of irradiance (spectral response of the sensor was between 400-1100 nm) when the EC was tinted during the summer.

*Condensation*

EnergyPlus was also used to determine the level of condensation that would occur in the room. Although interior surface temperatures were low, there were not a significant number of hours when temperatures were lower than the room air dewpoint temperature. Over the course of the year, there were 18.25 h and 21.25 h when condensation occurred on the inside surface of the existing window and frame, respectively. With the EC window, condensation never occurred. This may be due in part to the low nighttime setback temperature (12.8°C, 55°F).

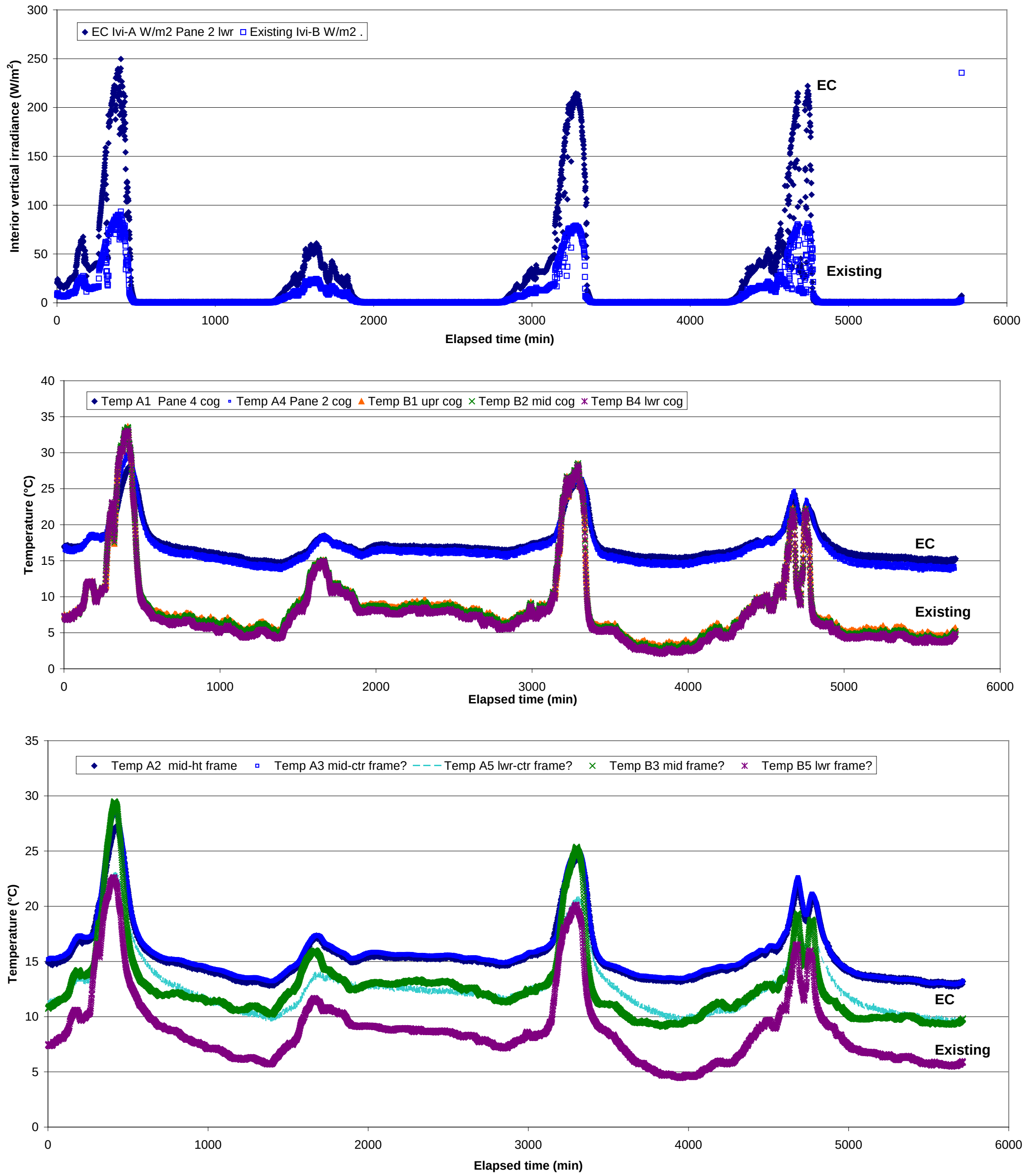



**Fig. 8.** Measured site data (December 17-21, 2010). Top: transmitted radiation through the EC window (case A) and existing window (case B). Middle: indoor glass surface temperature of the EC and existing window. Bottom: surface temperature of the EC and existing window frame.

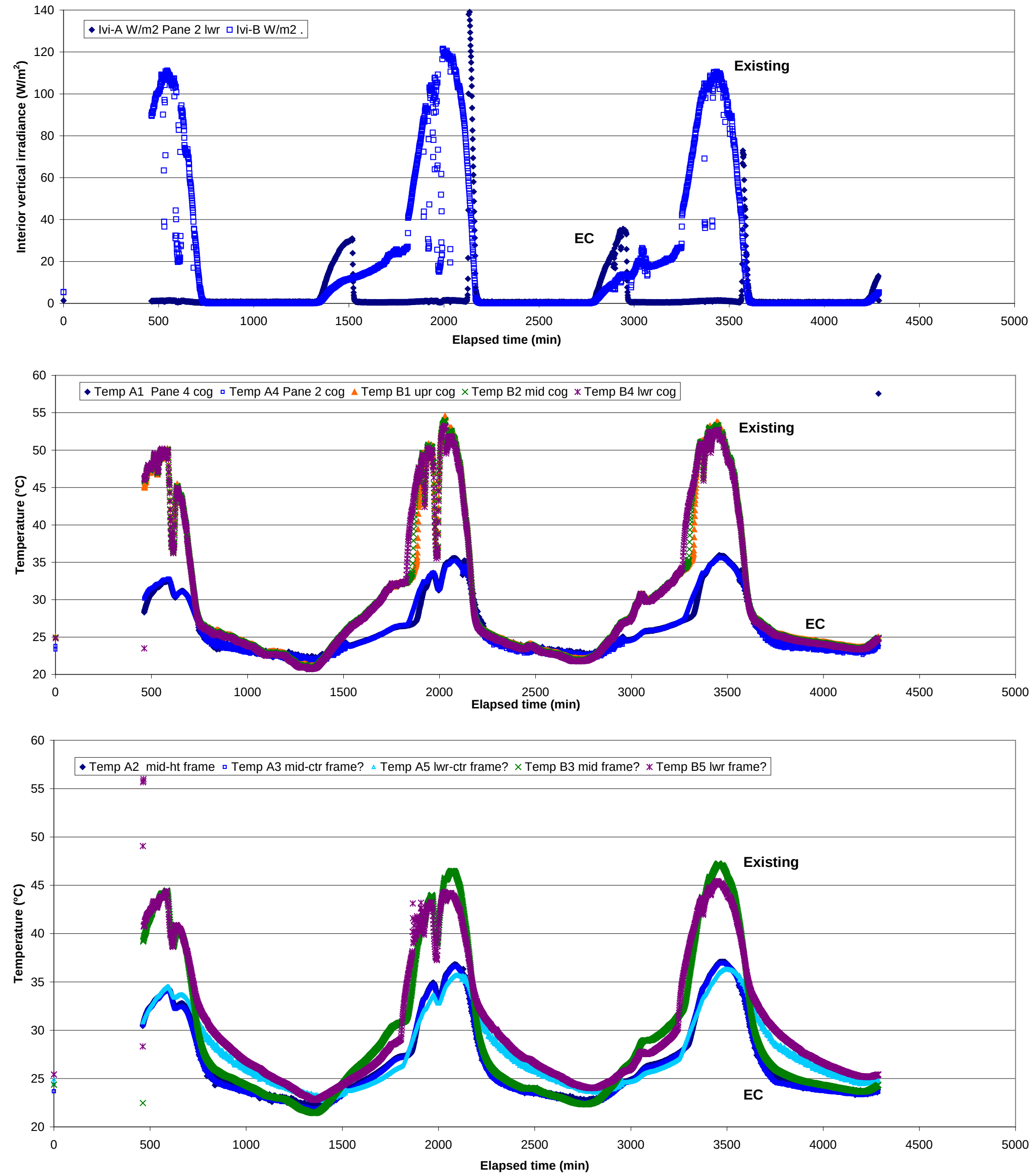



**Fig. 9.** Measured site data (August 6-9, 2010). Top: transmitted radiation through the EC window (case A) and existing window (case B). Middle: indoor glass surface temperature of the EC and existing window. Bottom: surface temperature of the EC and existing window frame.

### *5.2. Thermal discomfort*

EnergyPlus was used to determine the predicted percentage dissatisfied (PPD) occupants with the thermal conditions in the room for occupied weekday hours over the year. The Fanger Comfort Model within EnergyPlus was used [12] with the surface-area weighted method, modeling the discomfort level of a person sitting 0.91 m (3 ft) from the window. The average annual difference between the existing and EC windows was 3-5 PPD with PPD levels of 18%, 13%, and 15% for the existing, EC-clear, and EC-tinted windows. For the periods when PPD was greater than 20%, discomfort occurred under cold conditions (outdoor average temperature was 4-9°C, 40-48°F). There were 644 h or 7% of the year when PPD was greater than 20% with the existing window condition. There were 474 h or 5% of the year when PPD was greater than 20% with the EC window in its tinted state.

## 6. Energy use

### *6.1. Measured lighting energy use*

Lighting amperage was monitored using a self-powered current transducer (Veris Hawkeye), which was sampled every 1 s, averaged, and recorded every 1 min over each 24-h day. Amperage was converted to energy use by multiplying the current by the product of the estimated voltage (277 V), the power factor of the ballast (0.95), and a calibration scalar. Bench-scale tests were conducted to characterize measurement errors.

Four reference conditions and one test condition were defined as follows (Table 8):

- Reference 1: Existing conference room lighting condition, where the lights could not be turned off independently from the open plan office area outside the conference room.
- Reference 2: Existing condition (Reference 1) with an occupancy sensor. The occupancy rate was determined by computing the average weekday hours of occupancy over a 24-h period for the six-month monitored period. The occupancy sensor reduced Reference 1 lighting energy use by 68%.
- Reference 3: ASHRAE 90.1-2007 Standard for a conference room with an occupancy sensor, where the Space-by-Space Method was used to meet the prescriptive requirements for installed lighting power density (LPD). This combination yielded an 83% reduction in energy use compared to Reference 1.
- Reference 4: The actual retrofit condition with non-dimmable ballasts and an occupancy sensor. The lower installed lighting power density (LPD) yielded a lower workplane illuminance (322.8 lux (30 fc) instead of 538 lux (50 fc)) than References 1-3. Combined with an occupancy sensor, energy use was reduced by 87% compared to Reference 1 irrespective of the EC window.
- Test condition: Actual retrofit condition with dimmable ballasts and multi-scene, occupancy and daylighting controls.

Compared to Reference 1, the test condition produced monitored energy savings of 91%. The lack of significant additional savings (compared to savings with Reference 4) was due to the lower lighting power density and dimmable ballasts, which use more energy when in standby, shutoff mode compared to a non-dimmable ballast, in combination with the low occupancy rate of the conference room. Energy savings due to daylight through the EC window were counteracted by this increased load. Savings due to setpoint tuning could not be disaggregated from savings due to daylighting because the setting of the four-level lighting keypad could not be monitored. Because occupancy occurred at random times over the course of each day, the savings due to daylighting reflect an arbitrary sampling of sun and sky conditions.

The on-off switching of the EC windows resulted in less lighting energy savings than if the windows had been continuously modulated between the fully clear and tinted states. Even when conditions were sunny, the EC windows at the fully tinted state eliminated most useful daylight despite the large-area of the windows (WWR = 0.40). The visible transmittance of the fully tinted state, Tv, was 0.03. If the EC window transmittance could be modulated, more daylight could be admitted with a higher Tv level (within glare constraints) and the lighting could be dimmed down more.

Annual energy use projections given in Table 8 were determined by extrapolating the average weekday energy use per day to a full year, assuming no energy use on weekends and holidays. For low-occupancy spaces such as a conference room, this solution reduced annual lighting energy use from 65.6 to 6.1 kWh/m$^2$-yr (6.10 to 0.57 kWh/ft$^2$-yr) (91%).

**Table 8. Weekday Lighting Energy Use**

| Case | Installed LPD ($W/m^2$) | Standby power (W) | Workplane illuminance (lux) | Occ sensor? | Avg hours of weekday occupancy (h/24h-day) | Power use when occupied | Daylight controls? | Lighting energy use 24-h weekday $MJ/m^2$-day | Source Lighting Energy Use $MJ/m^2$-yr | Savings from Ref 1 (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ref1 | 26.47 | 0 | 510 | no | 10.00 | 100% | no | 0.95 | 864.01 | - |
| Ref2 | 26.47 | 0 | 510 | yes | 3.18 | 100% | no | 0.30 | 274.85 | 68% |
| Ref3 | 14.00 | 0 | 510 | no | 10.00 | 100% | no | 0.50 | 457.05 | 83% |
| Ref4 | 11.19 | 0 | 320 | yes | 3.18 | 100% | no | 0.13 | 116.20 | 87% |
| Test | 11.19 | 9 | | yes | 3.18 | variable | yes | 0.09 | 81.04 | 91% |

### *6.2. EnergyPlus simulations of perimeter zone annual energy use and peak demand*

Heating, ventilation, and air-conditioning (HVAC) energy use due to the EC window and lighting systems were not monitored in the actual conference room. Therefore, total annual energy use needed to be determined using simulations. The COMFEN 3.1 software tool [13], which is a fenestration-specific front end interface to the EnergyPlus building energy simulation program, was used to estimate energy use for a middle floor perimeter zone in a typical small office building. The geometry of the perimeter zone matched that of the actual conference room. The zone was served by a conventional single-zone packaged heating, ventilating, and air-conditioning (HVAC) system with a COP of 2.78 and gas burner efficiency of 0.74.

For the existing condition, the windows and lighting system met the ASHRAE 90.1-2007 code with the exception of the window U-value. Window size, type, layout, and orientation matched that of the actual conference room. The SHGC and WWR of the existing window were coincidentally the maximum values permitted by the ASHRAE 90.1-2007 standard for this climate zone 4A (code: SHGCmax = 0.40, WWRmax = 0.40). The U-value of the existing window did not meet code (U-code = 2.27 $W/m^2$-°C (0.40 Btu/h-$ft^2$-ºF), U-existing = 5.34 $W/m^2$-°C (0.94 Btu/h-$ft^2$-ºF)). Each window was modeled without and with a medium-colored interior fabric shade to gauge savings relative to code and an occupied existing condition. For the case with the shade, the shade was lowered fully over the window for all hours of the day. The lighting power density (LPD) of the existing lighting system was 14.0 $W/m^2$ (1.3 $W/ft^2$) (90.1-2007 Building Area Method for a conference room) and was non-dimmable. No controls are required by code if multi-scene control is provided, so lighting was assumed to be turned on during work hours: lighting power use was 100% from 8:00-17:59 LT and zero from 18:00-7:59 LT on work days. Power use was zero on weekends.

For the test condition, the windows and lighting system were the same as that installed in the conference room but no interior shade was modeled. The EC windows were switched using the same control algorithm as the actual conference room with a few exceptions. Zone exterior vertical irradiance was used to trigger EC switching within EnergyPlus, not exterior vertical illuminance because this trigger was not available in EnergyPlus. The equivalent switching thresholds were determined by correlating vertical illuminance to vertical irradiance using measured data under clear sky conditions: 233 $W/m^2$ and 91 $W/m^2$ for the upper and lower windows, respectively. For the occupancy controls, an occupancy level of 50% was modeled on weekdays between 8:00-18:00 LT by alternating between unoccupied and occupied status every other hour (5 h per day occupied). This higher level of occupancy seemed more reasonable for a typical conference room. During unoccupied periods, the EC was controlled to minimize HVAC use.

During occupied periods, the EC was controlled to minimize glare and admit daylight.  The installed LPD was 10.8 W/m$^2$ (1.0 W/ft$^2$) and the lighting system had photoelectric dimming controls based on available daylight 3.05 m (10 ft) from the window, 0.76 m (2.5 ft) above the floor, and centered on the two windows.  When daylight illuminance levels exceeded 377 lux (35 fc), the lights were dimmed in proportion to available daylight with a power range of 20-100% and light output of 5-100%.  When occupied, daylight dimming was in force.  When unoccupied, lighting power use dropped to standby levels (58.5 Wh) without delay.

Annual cooling, fan, and lighting electricity use were converted to source energy use using a site-to-source multiplier of 3.18.  Savings are given in Table 9.  Annual heating energy use savings were 47-63% due to passive solar heating during the winter when the room was unoccupied and the thermally-advanced window and framing system.  Cooling energy use savings of 24-34% were due to lower window and lighting heating gains.  Fan energy use was reduced by 35-52%.  Lighting energy use savings were 49% due to the daylighting and occupancy controls.  Total annual source energy use savings were 39-48% compared to the existing condition.  Peak electric demand was reduced by 22-35% to levels of 53.8 W/m$^2$-floor (5.0 W/ft$^2$-floor) for this 4.57 m (15 ft) deep space.

The EC windows required power to switch and maintain the bleached or tinted state of the windows. Power consumption of the EC varies depending on whether the window is in the process of being switched or being held constant at the tinted level.  Based on measurements in prior tests for the same device [14], peak power consumption was 2.8-3.4 W/m$^2$-glazing (0.26-0.32 W/ft$^2$) when the glass was being switched and 10.8-1.6 W/m$^2$-glazing (0.07-0.15 W/ft$^2$) when the glass was kept at a static state.  This includes power to the window, electronic circuitry for control, and parasitic losses due to the efficiency of the power supply.  If one assumes a peak power consumption level of 3.4 W/m$^2$-glazing (0.32 W/ft$^2$), 51 weeks, 10 h/day, then the total source energy use is increased by 30 MJ/m$^2$-year (2.6 kBtu/ft$^2$-year) and savings are reduced by 3%.  If a steady-state power consumption level of 1.6 W/m$^2$-glazing (0.15 W/ft$^2$) is assumed for 51 weeks and 10 h/day, then the difference is 1%.  Data for the former, more conservative scenario are given for total energy and peak demand in Table 9.

**Table 9.  Annual source energy use and peak demand**

| Annual energy use (MJ/m$^2$-yr) | Existing window No shade | Existing window Shade always down | EC window with daylighting controls | Savings No shade | Savings Shade |
|---|---|---|---|---|---|
| Heating | 128 | 89 | 47 | 63% | 47% |
| Cooling (source) | 340 | 298 | 226 | 34% | 24% |
| Fan (source) | 424 | 312 | 202 | 52% | 35% |
| Lighting (source) | 460 | 460 | 234 | 49% | 49% |
| Total Energy (source) | 1353 | 1159 | 708 | 48% | 39% |
| Total with EC Power (source) | 1353 | 1159 | 738 | 45% | 36% |
| Peak demand (W/m$^2$) | 83 | 70 | 54 | 35% | 22% |
| Peak demand with EC power (W/m$^2$) | 83 | 70 | 55 | 34% | 21% |

## 7. Conclusions

A pilot demonstration of dual-pane, switchable electrochromic (EC) windows, advanced thermally-improved window frames, and dimmable lighting systems was conducted in a conference room of an existing office building in Washington DC.  The EC windows were controlled to minimize seasonal heating and cooling loads, provide daylight, and minimize the effects of direct sun and discomfort glare.  When occupied during the day, the upper EC clerestory zone was switched to provide daylight and the lower zone was switched to minimize discomfort glare.  When unoccupied during the day, the smaller upper windows were switched to clear or tinted to minimize heating and cooling loads, respectively, and the lower larger windows were switched to tinted in anticipation of being required to switch to tinted due to discomfort glare, which can take some time. During the night, all windows were switched to clear.

Monitored data showed that significant performance benefits can be attained over the existing, single-pane, tinted window and non-controlled electric lighting system in this case study:

1. Monitored weekday lighting energy use savings were 91% compared to the existing condition over a six-month solstice-to-solstice period. Due to the low occupancy rate of the conference room, savings were largely due to the occupancy-based controls, lower setpoint, and the lower installed lighting power density. Without occupancy-based lighting controls, EnergyPlus simulations indicate that annual lighting energy use savings would be 35% due to daylighting alone.

2. Total annual energy use savings were estimated in EnergyPlus to be 39-48% compared to the existing condition due to passive solar heating during the winter, solar gain exclusion during the summer, reduction of thermal conduction through the window and frames, and reduction of lighting energy use through daylighting.

3. Peak electric demand was estimated in EnergyPlus to be reduced by 22-35% compared to the existing condition to levels of 53.8 W/m$^2$-floor (5.0 W/ft$^2$-floor).

4. EnergyPlus simulations indicated that the predicted percentage dissatisfied with the thermal environment was reduced from 18% with the existing un-insulated, single-pane windows to 13% and 15% with the clear and tinted dual-pane, argon-filled, EC windows and thermally-improved, low-e, aerogel-filled window frames, respectively. Simulated indoor surface temperatures of the EC window were 13-14°C (23-25°F) on average warmer than the indoor glass surface temperatures of the existing window during daytime work hours when it was cold and cloudy outside. Measured data for a few cold winter days were within this same range. On sunny hot days, simulated indoor surface temperatures of the EC window were almost the same as the existing window. Measured data for a few hot summer days, however, indicated that the indoor surface temperature of the EC window was significantly lower than that predicted by EnergyPlus, possibly due to differences in environmental conditions or errors in the thermistor reading due to solar irradiance. Simulations indicated that condensation at the window was eliminated.

5. The occupants did not use the manual switches to override the automated control system very often. This may be due to not understanding how to use the switches, despite the clear signage and ready access to project staff, or other factors related to the design of the manual switches and slow response of the electrochromic windows. However, given the proactive, vocal nature of the end users, it is likely that the group of occupants that used this conference room did know how to use the switches and used them deliberately. Of the 328 meeting that occurred over the six-month period, the manual switches were used during 14 of these meetings for reasons other than demonstration of the EC window technology. When the automatic system was overridden, 79% were made when the occupant first entered the room, 26% were made to fix the EC windows to the state they were already in (often when first entering the room), and 36% were likely made to demonstrate the EC window switching capabilities. On some occasions, occupants switched the window in a manner that suggested that they desired more daylight than that provided by the automatic control system: i.e., one upper zone was left clear while the remaining zones were tinted. The occupants could alter the interior Venetian blinds if the electrochromic windows did not provide comfortable conditions. The blinds were lowered occasionally over the upper window zone during some of the monitored period, possibly to reduce the luminance contrast between the upper clear zone and the lower tinted zone.

6. The occupants had a completely unobstructed view out the lower windows over the entire six-month monitored period because they did not fully lower the blinds. An opposing building across the street blocked low angle sun to this western exposure. Discomfort glare appeared to be adequately controlled by the tint level of the lower EC windows to warrant non-use of the blinds.

7. Fault detection and diagnostic (FDD) tools are indispensable for troubleshooting automatic control systems. This pilot demonstration provided insights into what data and infrastructure are needed to detect problems with the control system, sensors, and associated hardware.

Further studies are needed in a more extensive application of EC windows with measured environmental data and subjective response data to better understand user acceptance and satisfaction with this technology.

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